3-D Center-Weighted Vector Directional Filters for Noisy Color Sequences

Rastislav LUKÁČ
Dept. of Electronics and Multimedia Communications
Technical University of Košice
Park Komenského 13, 041 20 Košice
Slovak Republic

Abstract

This paper focuses on a noise filtering in color image sequences, where a new class of center-weighted vector directional filters is provided. According to high dimensionality of color image sequences, where besides the spatial frequencies in the frames it is necessary to consider the temporal correlation of an image sequence and the correlation between color channels too, the processing of color image sequences represents very important and interesting problem. Clearly, the color image sequences represent three-dimensional (3-D) vector-valued image signals and thus, the 3-D vector filters provide optimal approach, only. Novelty of this paper lies in the impulse noise suppression by a new class of center-weighted vector directional filters, where the influence of the filter parameter to filter performance is analyzed. The interesting behavior of a new filter class is illustrated by a number of experimental results and comparisons with the well-known filtering algorithms for color image sequences.

Keywords

Color image sequences, vector filters, directional processing, weight vector, impulse noise

1. Introduction

In this paper, a new nonlinear filter class for the impulse noise filtering in color image sequences is presented. Namely, the three-dimensional (3-D) center-weighted vector directional filters with smoothing function controlled by tuning parameter controlling the center weight are provided. In dependence on the tuning parameter, it allows to achieve the balance between the very noise suppression and signal-details preservation. Likewise, motion preservation and the reduction of color distortion can be observed, too. According to achieved results and the dimensionality of color image sequences, proposed class of 3-D center-weighted vector directional filters represents optimal filtering approach, where an estimate is formed as a sample from input set.

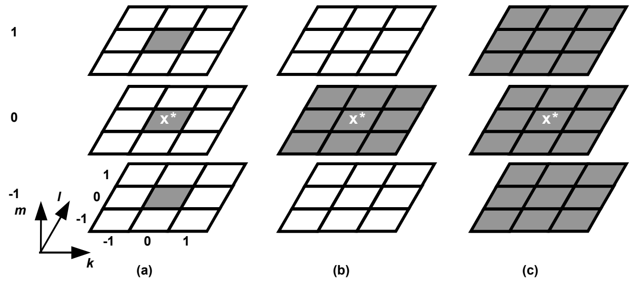

Fig. 1 Filtering methods for the image sequences divided according to a filter window dimensionality. a) Temporal (1-D) filters with a filter window of three samples placed along a time trajectory and thus, only the temporal correlation between the frames is considered. b) Spatial (2-D) filters with a filter window that spans the samples in the processed frame only, i.e. frames are processed independently. (c) Spatiotemporal (3-D) filters with a cube filter window and thus, input set includes both temporal correlation and spatial correlation of the samples.

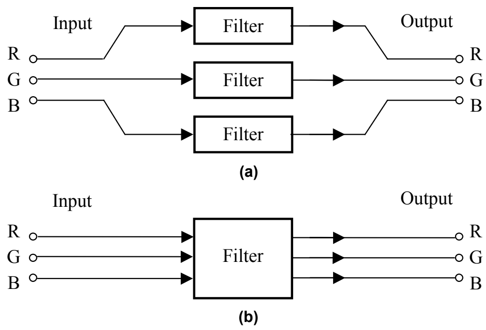

Fig. 2 Filtering methods for color images divided according to utilized correlation between color channels. a) Marginal (componentwise) filtering is based on the separate processing of color channels. In general, marginal processing produces new samples that result in color artifacts to which the human visual system is very sensitive. b) Vector processing uses the correlation between the color channels. For that reason, the vector methods represent the optimal and attractive approach for the study and the processing of color images.

The proposed method avoids to color artifacts and utilizes strictly a directional base. For that reason, it preserves the color chromaticity well. Besides the correlation between color channels, the algorithm of the proposed 3-D filters respects the inherent spatial correlation in frames and temporal correlation between individual frames. The sufficient performance of the proposed method is supported by a measure of the smoothing controlled by a filter parameter.

From Fig. 1 and Fig. 2 it can be seen that in the case of noisy color image sequences, optimal filtering method should incorporate the spatial correlation present in frames, the temporal correlation between frames and finally the correlation between color channels. For that reason, only 3-D vector filters will represent the approach, when a filter will process the color image sequence naturally to a signal dimensionality given by spatial co-ordinates, time trajectory and color information.

Though the well performance of 3-D vector filters is usually related to 3-D vector-median based filters, this paper shows results that the recently developed weighted vector directional filters, namely their subclass called center-weighted vector directional filters can be used successfully in tasks of impulse noise suppression in color image sequences [15] and multimedia applications [4], too.

2. A Class of Center-Weighted Vector Directional Filters

Let $y(x): Z^l \rightarrow Z^m$ represent multichannel image, where l is an image dimension and m characterizes a number of channels. If $m \geq 2$, then it is the case of m-channel image processing. In the case of standard color images l=2 and m=3. Let $W=\{\mathbf{x}_i \in Z^l;\ i=1, 2\ldots, N\}$ represent filter window of a finite size N, where $\mathbf{x}_1,\mathbf{x}_2,\ldots,\mathbf{x}_N$ is a set of noised samples. Note, that the position of filter window is determined by the central sample $\mathbf{x}_{(N+1)/2}$. Each input vector $\mathbf{x}_i$ is associated with the angle distance α_i [7], [12] that is defined by

$$\alpha_i = \sum_{j=1}^{N} \mathrm{A}(\mathbf{x}_i, \mathbf{x}_j) \quad \text{for } i = 1,2,...,N \tag{1}$$

where

$$\mathrm{A}(\mathbf{x}_i, \mathbf{x}_j) = \cos^{-1}\left(\frac{\mathbf{x}_i.\mathbf{x}_j^T}{|\,\mathbf{x}_i\,|.|\,\mathbf{x}_j\,|} \right) \tag{2}$$

represents the angle between two m-dimensional vectors $\mathbf{x}_i=(x_{i1},x_{i2},\ldots,x_{im})$ and $\mathbf{x}_j=(x_{j1},x_{j2},\ldots,x_{jm})$. If angle distances (1) serve as an ordering criterion, i.e.

$$\alpha_{(1)} \leq \alpha_{(2)} \leq ... \leq \alpha_{(r)} \leq ... \leq \alpha_{(N)} \tag{3}$$

then it means that the same ordering is implied to input set $\mathbf{x}_1,\mathbf{x}_2,\ldots,\mathbf{x}_N$ which results in ordered input sequence

$$\mathbf{x}^{(1)} \leq \mathbf{x}^{(2)} \leq ... \leq \mathbf{x}^{(r)} \leq ... \leq \mathbf{x}^{(N)} \tag{4}$$

If a filter output is given by the sample from input set that minimizes the sum of angles with other vectors, then filter performs filtering operation equivalent to a basic vector directional filter (BVDF) [3], [7], [12], [14], i.e.

$$\mathbf{y}_{BVDF} = \mathbf{x}^{(1)} \tag{5}$$

where sample $\mathbf{x}^{(1)}$ is associated with minimal angle distance $\alpha_{(1)}$

Let $\mathbf{x}_1,\mathbf{x}_2,\ldots,\mathbf{x}_N$ be an input set determined by a filter window and $w_1,w_2,\ldots,w_N$ represent a set of nonnegative integer weights so that each weight w_j, for j=1,2,…,N, is associated with the input sample $\mathbf{x}_j$. Then the weighted angle distance β_i associated with the input sample $\mathbf{x}_i$ is given by

$$\beta_i = \sum_{j=1}^{N} w_j \mathrm{A}(\mathbf{x}_i, \mathbf{x}_j) \quad \text{for } i = 1,2,...,N \tag{6}$$

where $\mathrm{A}(\mathbf{x}_i,\mathbf{x}_j)$ is the angle (2) between two m-dimensional vectors $\mathbf{x}_i$ and $\mathbf{x}_j$.

The output of weighted vector directional filter (WVDF) if given by the sample associated with minimal weighted angle distance $\beta_{(1)}$ according to

$$\beta_{(1)} \leq \beta_{(2)} \leq ... \leq \beta_{(r)} \leq ... \leq \beta_{(N)} . \tag{7}$$

The WVDF provides more significant variety of filtering operations than the BVDF filter. In addition, a class of WVDF includes many interesting vector directional filters as special cases. For example, if all weights are set to 1, i.e. $w_j=1 (j=1,\ldots,N)$, then WVDF is equivalent to BVDF.

The more interesting filter class is represented by center-weighted vector directional filters (CWVDF), where the weights associated with neighboring samples are refered as the ones while the center weight $w_{(N+1)/2}$ is forced to be an odd nonnegative integer value from 1,3,…,N. Note that N is a window size. In order to simplify the understanding of CWVDF filtering operation, consider a tuning parameter k [9] and the CWVDF with a window size N. The tuning parameter is restricted to be an integer between one and $(N+1)/2$, i.e. $k=1,2,\ldots,(N+1)/2$.

Since all neighboring weights are equal to one, the weight vector $\{w_1, w_2, \ldots, w_N\}$ can be defined as follows

$$w_j = \begin{cases} N - 2k + 2 & \text{for } j = (N+1)/2 \\ 1 & \text{otherwise} \end{cases} \tag{8}$$

Then, the output of CWVDF is given by [7]

$$\mathbf{y}_k = \mathbf{x}^{(1)} \tag{9}$$

where $\mathbf{x}^{(1)}$ (4) is ordered vector-valued sample associated with a minimal weighted angle distance $\beta_{(1)}$ (7) according to weight vector (8) and the input set $\mathbf{x}_1,\mathbf{x}_2,\ldots,\mathbf{x}_N$. In the dependence on the tuning parameter k, the CWVDF can provide a wide range of smoothing characteristics from an identity filter to that of the BVDF. If the tuning parameter k is equal to 1, then CWVDF is equivalent to identity filter, i.e. no smoothing is performed and the central sample $\mathbf{x}_{(N+1)/2}$ is passed to a filter output without the change. The maximum amount of smoothing, i.e. BVDF filtering operation is performed while the tuning parameter k is equal to its maximum possible value, i.e. $(N+1)/2$. The balance between the noise smoothing and the signal-details preservation can be achieved when the tuning parameter k is set between 1 and $(N+1)/2$.

It can be seen that the main advantage of the CWVDF in comparison with the WVDF lies in the fact that the CWVDF is controlled by one parameter only, whereas the performance of WVDF depends on N weights. For that reason, the filtering structure of the CWVDF is simpler significantly. The dependence of the CWVDF performance on the tuning parameter k is showed in the next Section that starts with the vector definition of the impulse noise.

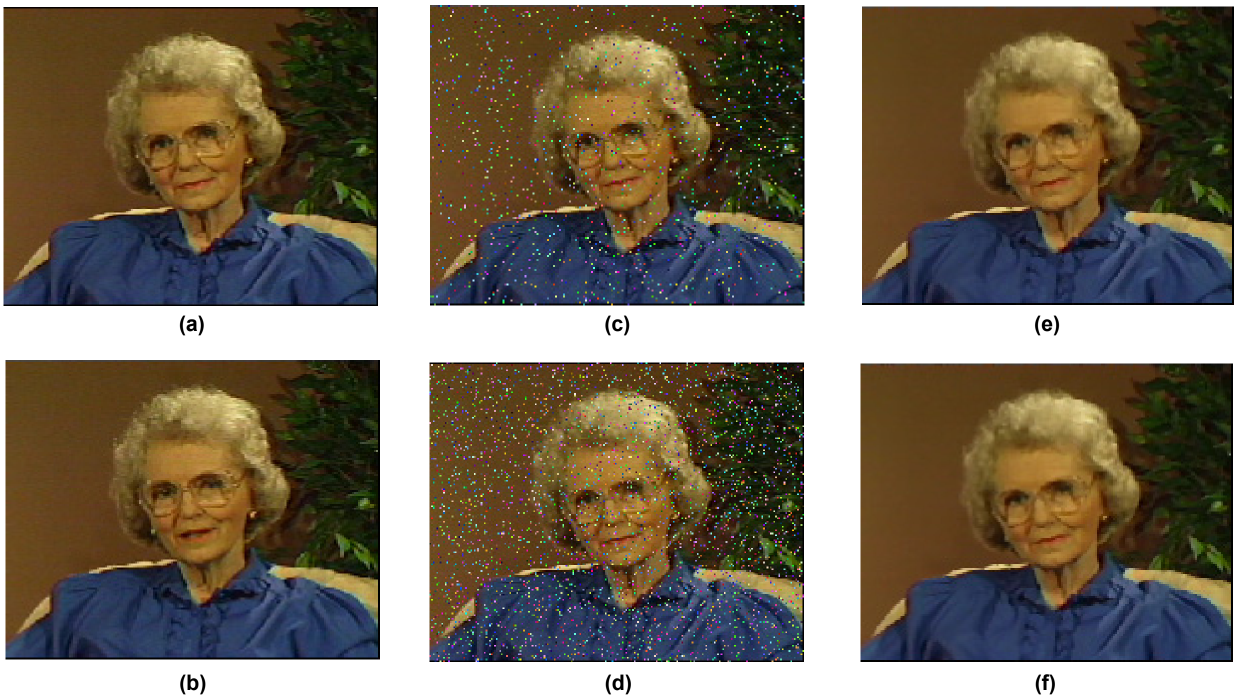

Fig. 3 Frames of the test color image sequence "Grandmom". a) Original 5th frame b) Original 95th frame c) 5th frame corrupted by 5% impulse noise (p = 0.05) d) 5th frame corrupted by 10% impulse noise (p = 0.1) e) 10% impulse noise filtered by 3-D vector median f) 10% impulse noise filtered by 3-D extended vector median.

3. Experimental Results

To get an unbiased view on a filter performance, as the test signals were used several color image sequences with various statistical properties. In order to save the place, in this paper there are presented results related to the color image sequence "Grandmom" which is an appropriate representative of the used test set. This sequence consists of 99 frames with a resolution of 300×240 samples and an 8 bits per sample representation for each color channel. In Fig. 3a and Fig. 3b are showed 5th and 95th frames.

In general, mathematical model of the impulse noise for the color images can be expressed as [11]

$$\mathbf{x}_{i,j} = \begin{cases} \boldsymbol{\upsilon} & \text{with probability } p \\ \mathbf{o}_{i,j} & \text{with probability } 1-p \end{cases} \qquad (10)$$

where i, j characterize sample position, $\mathbf{o}_{i,j}$ is the sample from the original image, $\mathbf{x}_{i,j}$ represents the sample from the noisy image, p is a corruption probability and $\boldsymbol{\upsilon}$ = = $(\upsilon_R, \upsilon_G, \upsilon_B)$ is a noise vector of intensity random values. Since components of $\boldsymbol{\upsilon}$ are generated independently, the gray impulse, i.e. all components of $\boldsymbol{\upsilon}$ are equivalent $(\upsilon_R = \upsilon_G = \upsilon_B)$, can occur in the special case, only.

As a measure of the noise corruption and the filter performance, too, four objective criteria, namely mean absolute error (MAE), mean square error (MSE), cross correlation (ΔR) [8] and color difference (CD) [13], are used. In general, MAE is a mirror of the signal-details preservation, MSE well evaluates the noise suppression, ΔR expresses the preservation of the motion trajectory in the image sequence and CD is a measure of the color chromaticity preservation. Thus, the quality of the processed image sequences is quantified with a high accuracy related to the signal dimensionality.

Concerning the performance (Fig. 3e, f, and Fig. 4a, b) of usually used vector filters [17] such as standard vector median (VM) [2], [6], [11], extended VM [2], [15] and weighted VM [6], [11], [15] the proposed CWVDFs can be said to be useful for the impulse noise filtering in color image sequences. More, the error criteria CD achieved by CWVDF is significantly better than that of the vector median-based filters. Next, the performance of CWVDF in dependence on a filter parameter is shown in Fig. 5, Fig. 6, Tab. 1 and Tab. 2.

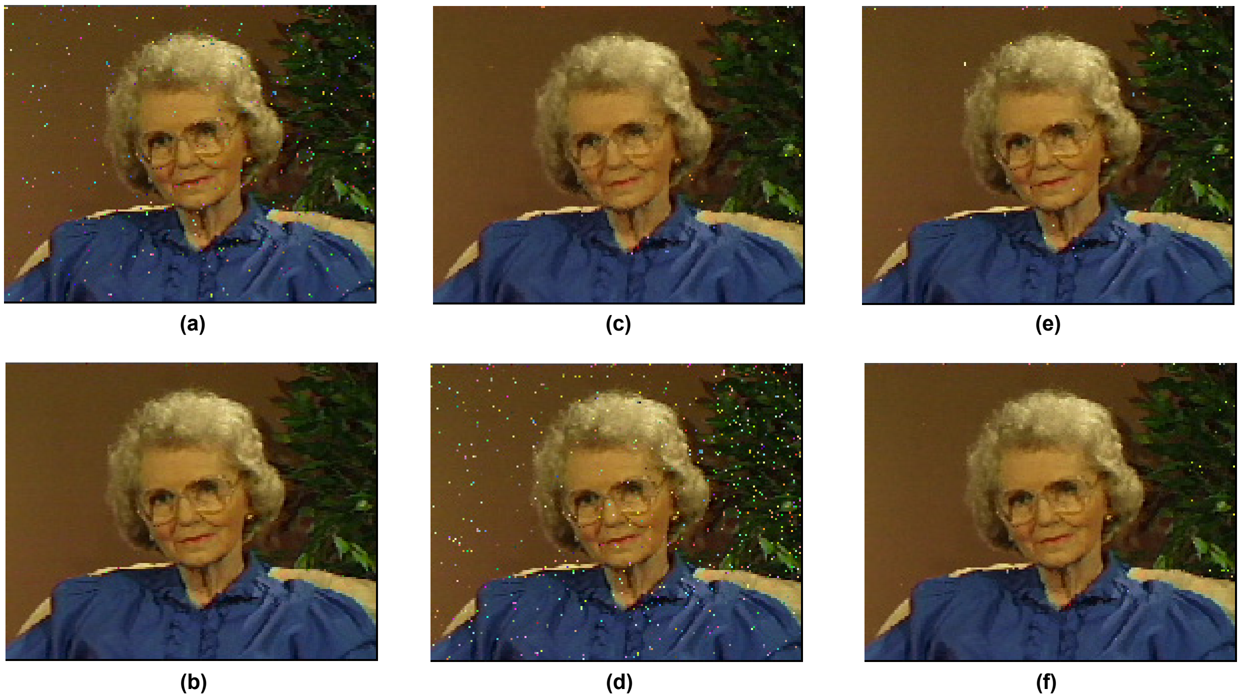

Fig. 4 10% impulse noise suppressed by a) 3-D center weighted vector median (k = 4) b) 3-D center weighted vector median (k = 7) c) 3-D BVDF (CWVDF k = 14) d) 3-D CWVDF (k = 4) e) 3-D CWVDF (k = 7) f) 3-D CWVDF (k = 10).

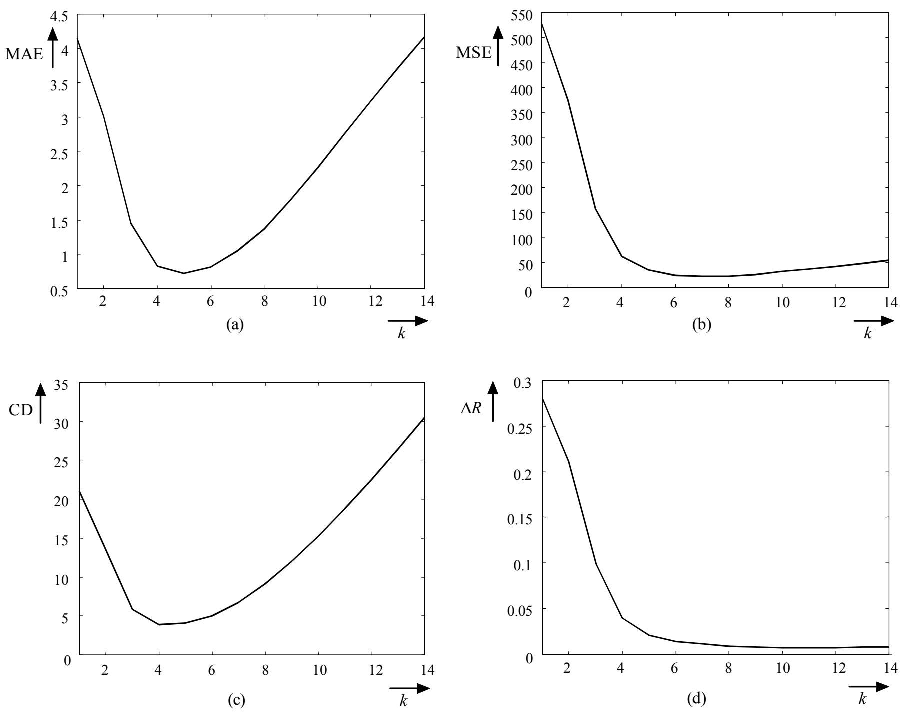

Fig. 5 Dependence of error criteria on tuning parameter k for the impulse noise with p = 0.05. a) Mean absolute error b) Mean square error c) Color Difference d) Cross correlation

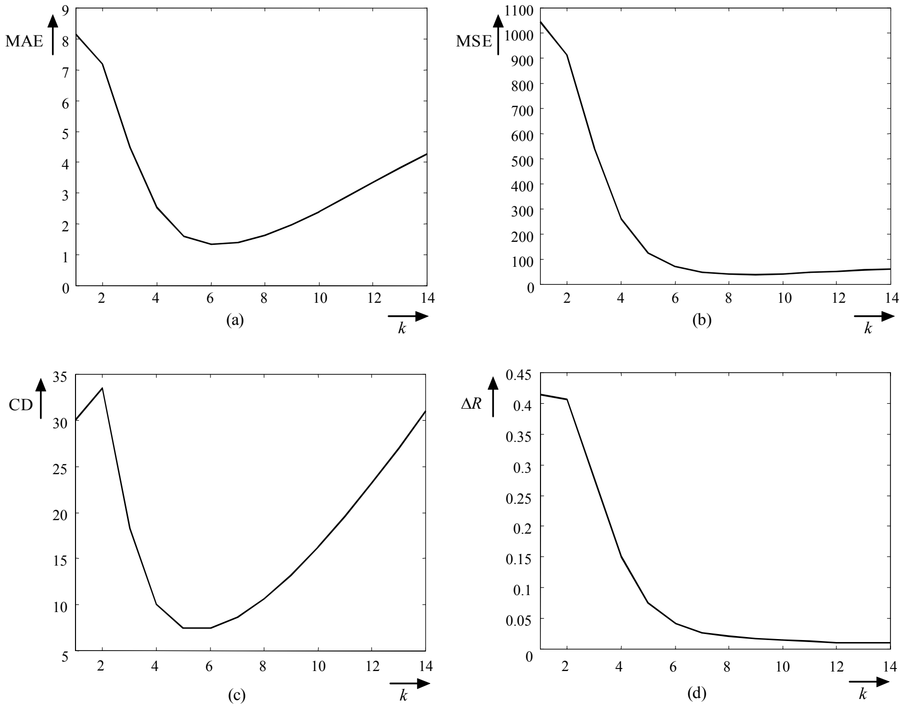

Fig. 6 Dependence of error criteria on tuning parameter k for the impulse noise with p = 0.1. a) Mean absolute error b) Mean square error c) Color Difference d) Cross correlation.

Method	MAE	MSE	CD	ΔR
identity	4.150	529.2	21.061	0.281
vector median (VM)	3.086	22.7	30.436	0.005
extended VM	3.093	22.6	30.553	0.005
CWVDF (k = 2)	1.455	158.0	5.813	0.099
CWVDF (k = 3)	0.831	63.6	3.871	0.040
CWVDF (k = 4)	0.725	34.7	4.055	0.021
CWVDF (k = 5)	0.816	24.7	5.044	0.014
CWVDF (k = 6)	1.046	22.2	6.806	0.011
CWVDF (k = 7)	1.372	22.1	9.169	0.009
CWVDF (k = 8)	1.372	22.1	9.169	0.009
CWVDF (k = 9)	1.785	25.4	12.027	0.008
CWVDF (k = 10)	2.262	31.5	15.334	0.007
BVDF (CWVDF for k = 14)	4.173	55.5	30.517	0.008

Tab. 1 Evaluating of the experimental results for the impulse noise corruption p = 0.05

Clearly, a noise attenuation capability of CWVDFs increases with the increased tuning parameter k or the center weight $w_{(N+1)/2}$. The small amount of the smoothing results in the impulse presence (Fig. 4d), whereas to much smoothing given by CWVDF with a high value of k or $w_{(N+1)/2}$ can introduce a signal blurring.

4. Conclusion

The paper focuses in a class of 3-D center-weighted vector directional filters (CWVDFs), where a filter performance is analyzed and discussed depending on the tuning parameter. These filters have been provided as a solution, especially for the impulse noise suppression in color image sequences. Since CWVDFs can perform a various amount of the smoothing from no smoothing to that of the BVDF, the proposed method is useful for a wide use in smoothing applications. If the tuning parameter is set between values 5 and 10, the proposed method provides the best balance between error criteria. The experimental results showed the improvement in comparison with traditional filters used for the filtering of noisy color image sequences. According to a number of samples spanned by a filter window, the future research tasks are related to a decimated filter structure.

Method	MAE	MSE	CD	ΔR
identity	8.133	1043.6	40.896	0.447
vector median (VM)	3.171	24.0	31.073	0.004
extended VM	3.177	24.1	31.143	0.004
CWVDF (k = 5)	1.607	125.3	7.474	0.075
CWVDF (k = 6)	1.348	71.7	7.503	0.042
CWVDF (k = 7)	1.396	49.4	8.651	0.027
CWVDF (k = 8)	1.635	42.2	10.625	0.021
CWVDF (k = 9)	1.979	40.1	13.181	0.017
CWVDF (k = 10)	2.414	43.1	16.272	0.015
CWVDF (k = 11)	2.881	48.2	19.603	0.013
CWVDF (k = 12)	3.347	51.6	23.184	0.011
CWVDF (k = 13)	3.822	56.8	27.005	0.010
BVDF (CWVDF for k = 14)	4.280	62.7	31.039	0.010

Tab. 2 Evaluating of the experimental results for the impulse noise corruption p = 0.1

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About authors...

Rastislav LUKÁČ (Ing., Ph.D.) received the M.Sc. (Ing.) degree with honors at the Technical University of Košice, the Slovak Republic, at the Department of Electronics and Multimedia Communications in 1998. In 2001 he finished Ph.D. study. The title of his dissertation work was „New structures of LUM smoothers and impulse detectors for noisy images“, in which he focused on the impulse noise suppression in monochromatic, color and multidimensional images. Currently, he is an assistant professor at the Dept. of Electronics and Multimedia Communications at the Technical University of Košice.

He is a co-author of the book „Digital filtering of image signal“ and some textbooks focused in electronics, multimedia systems and telecommunications. He is an author of over 60 scientific papers published in journals and conference proceedings. He was an organizer of the international scientific conference „Digital Signal Processing and Multimedia Communications 2001“.

Recently, his research interests include digital filters for multidimensional signals, use of Boolean functions and permutation theory in filter design, impulse detection, color image processing, image sequence processing, motion compensation, watermarking, and multimedia processing.

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